

STUDIES OF THE UTILIZATION OF WIND ENERGY:
THE USE OF DC GENERATOR/MERCURY-VAPOR INVERTER SETS
CONNECTED TO AC NETWORKS

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16. Abstract Different types of electrical generators are reviewed that can be used with wind energy. A set is described that is comprised of a generator supplied by a suitable type of excitation and a mercury-vapor inverter capable of incorporation in a three-phase network with constant voltage and frequency, provided with reservoirs, with power which is transmitted -- for any wind velocity -- by a fixed-pitch air motor without a speed regulator. Experimental results obtained with such a set are reported.			
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STUDIES OF THE UTILIZATION OF WIND ENERGY:
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1. Different Types of Generator Sets for the Utilization of
Wind Energy

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The utilization of wind energy through production of electrical energy can be applied to ac or dc generator sets. The first necessarily feed local networks, in general independent of other generators; by means of electrical accumulators, they allow the scheduled energy requirements to be adjusted to an irregular and discontinuous availability. However, the presence of accumulators in a production plant increases the installation costs and adds to the unit cost of the energy produced. The ac generator sets, however, permit connection to the common distribution networks: with these, energy accumulation systems can be avoided, since the accumulation reservoirs of the ac networks themselves serve such a purpose.

All types of ac generators can be used for this purpose; generator sets can also be utilized that are composed of dc machines and dc-ac energy converters. However, among the various types or sets of generators, some are less suitable than others, due to the rigid or almost rigid link that exists between their rotation speed and generation frequency, which must necessarily coincide with that of the network, and thus remain constant.

The ideal characteristic to be required from a generator or a set composed of more electrical machines can be studied with reference to the characteristics of the air motor that yield the law of power variation P as a function of the number of revolutions

*Numbers in the margin indicate pagination in the foreign text.

per minute n , for wind velocities w_v constant (Fig. 1).¹ By varying the wind velocity, the points corresponding to the maximum theoretical power P_{\max} are disposed on a cubic parabola. If it is considered that for every wind velocity the air motor shows a stability margin adapted with respect to the point of maximum theoretical power, which represents the limit of static stability of the set, it is seen that through this there can be fixed in the same Cartesian plane P - n of Fig. 1 a curve with a shape close to that of a cubic parabola, according to which the air motor becomes operational. Taking into account the proportionality existing between the rotation speed of the air motor and that of the electrical generator controlled by it, in general, by an overdrive, the existence of an ideal characteristic P - n is deduced also for the generator; this has the approximate shape of a cubic parabola. A generator that offers such a characteristic allows the most simple utilization and incorporation into the network of the power of the fluid vein at any velocity that crosses the section described in motion by the propeller blade, making use of a fixed-pitch air motor, with no provision for a speed regulator.

Among the different types of ac generators, the synchronous and the asynchronous have a characteristic far removed from the ideal. The former, in plane P - n of Fig. 1, have a characteristic coinciding with a vertical line. The latter, a characteristic coinciding with a line slightly inclined with respect to the vertical, as a consequence of slippage, that increases with an increase in the power. These generators require the use of variable-pitch air motors supplied with speed regulators.

¹For two wind velocities w_{v0} and w_{v1} , the latter greater than the former, Fig. 1 shows the relative values of P and n , referred to those values P_n , n_n , corresponding to a condition assumed to be normal. For velocities lower than w_{v0} , the P characteristic contracts, remaining included within that relative to w_{v0} .

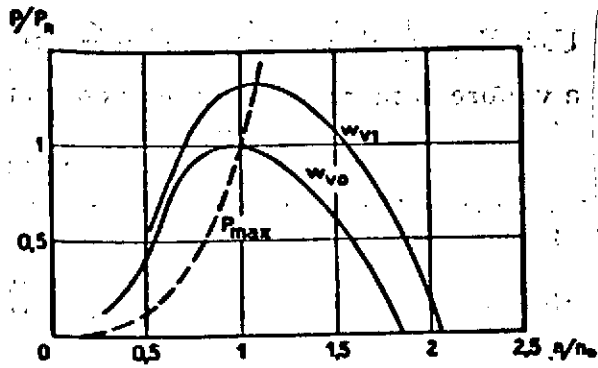


Fig. 1. Mechanical characteristics of an air motor and ideal characteristic of an electrical generator set.

A type of ac generator that allows a characteristic of the ideal type to be obtained is constituted by the Schrage machine, studied recently in this application [1]. However, it is not suited to attain considerable power, nor is the solution of the problem of speed regulation simple; this regulation is obtained by the relative displacement of the two systems of brushes arranged on the commutator.

More convenient is the group composed of an asynchronous machine in cascade with a commutator. With suitable hookups and excitations, in plane P-n of Fig. 1. the characteristic of this set coincides with a line inclined with respect to the vertical (rotation speed increasing with power increase), and it can come very close to the trunk of the ideal parabolic characteristic in question.

Another set that was also studied for this purpose is one composed of a synchronous generator and a mercury-vapor frequency converter. The converter adapts the variable frequency of the generator, moved at variable speed by the air motor, to the constant frequency of the network.

Finally, still within the scope of allowing a variable generator speed, but with a constant frequency (and voltage) of the three-phase network, there can be recourse to sets composed of suitably excited dc generators and dc-ac converters. The converter can be rotary, comprised of a dc motor and a synchronous

generator: by a suitable choice of the type of excitation of the two dc machines, the desired ideal characteristic can be obtained [2].

More simply, a mercury-vapor converter can be used that operates from an inverter, across which the dc machine is connected with a three-phase network, kept at constant voltage and frequency by the synchronous machinery. The characteristic of the set can come very close to the parabolic ideal by exciting the generator in such a way that the characteristic of its voltage as a function of rotation speed assumes a suitable shape when linked to that of the current-voltage characteristic of the inverter.

The composition of such a generator set and the results that can be obtained from it by moving it at however variable a speed have been studied theoretically and experimentally at IEN, Turin, on the rotary machines of this Institute and on a mercury-vapor converter with a glass bulb, property of the CNR, acquired about 10 years ago and designed for tests on these types of converters. The results obtained were positive, and they show that the set in question can be used conveniently for the proposed purpose.²

2. Composition and Behavior of the Set

A type of voltage/rotation speed characteristic of the

²The author is grateful to the CNR which, at the suggestion of Prof. Luigi Lombardi, entrusted the converter in question (acquired in 1937) first to Prof. Lombardi himself and later to the writer in order to carry out tests on his mercury-vapor converters; these tests, suspended during the war and the postwar period, have now been resumed, beginning with those referred to. Heartly thanks are also due to Prof. Vallauri for having consented to carry out at the IEN in Turin the experiments in question, and for making available the rotary machines and necessary apparatus; and also to the colleagues at the IEN, particularly Prof. Carrer, for his kind help.

sort necessary can be obtained for the generator in the diagram in Fig. 2, in which the excitation -- independent and multiple -- is given by a metadyne E and an auxiliary generator e. The voltage v_0 that supplies the excitation to the exciters e, E is constant.

A similar diagram, without excitation winding S and the auxiliary exciter generator e was studied by Prof. Carrer [3] in order to obtain an ideally constant emf by varying the rotation speed of the group within wide limits. The addition of supplementary excitation winding S, fed by a small exciter e coaxial with

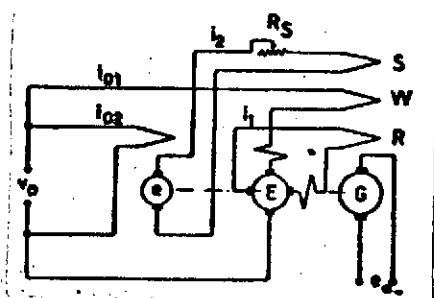


Fig. 2. Diagram of the set of rotary machines.

the generator, with independent and constant excitation, transforms (as can be seen [4]) the emf characteristic as a function of the rotation speed, ideally coincident with a horizontal line, into a characteristic that is first slowly and then more and more rapidly ascending:

at the original terminal of the emf, which is constant

when saturation of the magnetic

circuit is disregarded, a second one is added that is variable with the quadratic law as a function of the rotation speed of the set, especially when it is considered apart from the saturation of the magnetic circuit.

In practice, for the variable reluctance of this, the law /56 of variation in the emf of the generator, just as in the original diagram of Prof. Carrer, as well as in that of Fig. 2, undergoes changes; the emf decreases with a reduction in rotation speed to below a certain limit, until it is cancelled for zero rotation speed. However, the characteristic comes very close -- within wide limits of variation in the speed -- to the ideal, horizontal,

or first slowly and then more rapidly ascending, with an increase in the rotation speed itself; in the experimental set, with the diagram of Fig. 2, these limits are, respectively, 750-800 and 2000-2200 rpm.

Another diagram can also be adopted in place of that in Fig. 2, omitting the auxiliary winding W. The emf of the generator proves to be somewhat more rapidly variable than in the diagram of Fig. 2, especially at lower speeds. In toto, the diagram behaves in a way that is much the same as that of Fig. 2.

In each case, the voltage at the generator terminals under load follows a law analogous to that of the emf. The unidirectional current that the generator delivers toward the inverter is proportional to the difference between the voltage at the terminals of the generator itself and that rectified in the inverter. Given the shape of this characteristic at constant frequency and voltage of the three-phase network with which it is connected, for a constant value of angle α of lag in polarization of the command grids (the rectified voltage increases approximately linearly, ascending slowly with an increase in the rectified current), as it is easy to see³, the current delivered from the generator toward the inverter increases -- first slowly, and then more rapidly -- with the increase in rotation speed of the generator. With suitable proportioning of the machines' characteristics and excitations, it is possible to make the current supplied by the generator follow an increment law such that the corresponding power supplied by the generator to the inverter increases in turn as a function of the rotation speed according to a law close to the desired cubic parabola.

³See Ref. [illegible].

3. Experimental Results

The diagram in Fig. 2 as well as the simplified diagram without winding W have been designed and tested experimentally. The following machines were used for this purpose:

For generator G, we used a S. Giorgio metadyne of 21 kW, 150-160 V, 2000 rpm, adapted for generator operation, with the excitation windings indicated in Fig. 2.

For principal exciter metadyne E, the regulator of the S. Giorgio metadyne was used, transformed into a metadyne and able to supply at the principal winding R of the generator a maximum power of 132 W under a voltage of 11 V, at a speed of about 500 rpm; at higher speeds, the voltage and power required diminish.

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As supplementary exciter e, coupled coaxially with the previously mentioned machines, a dc machine was used, constructed by Marelli, with independent excitation and current that supplies a voltage of 6.5 V and a power of 260 W at the maximum speed reached, which is about 2000 rpm.

The set of three machines considered was moved by means of a dc motor a, with independent excitation, supplied at variable voltage so as to obtain a speed variation between 100 and about 2200 rpm. For voltage v_0 , there was recourse to accumulators. The value of v_0 most suited to supply characteristics of the desired shape was about 32 V; the maximum power supplied by the accumulators in the closed circuit is $32 \text{ V} \times 14 \text{ A} \approx 450 \text{ W}$.

As inverter the mercury-vapor converter of the CNR was used, to which we referred, designed to operate as a rectifier as well as an inverter. It is of CGE manufacture, provided with a glass bulb with six anodes, and was used in the two diagrams of three-phase

Y connection -- forked six-phase and three-phase Y -- dual three-phase with interphase inverter. The nominal rectified current is 50 A, the maximum rectified voltage at no-load operation of the rectifier without angle α of lag in grid polarization, 220 V with the forked six-phase diagram, about 125 V with the dual three-phase with interphase inductor; the transformer three-phase winding was Y-connected and joined with the urban three-phase network at 220 V, frequency 50 Hz. For operation of the inverter in connection with the generator considered, whose voltage is on the order of 60-80 V, the angle α of lag in grid polarization must be kept equal to $105-107^\circ$ in the tests with the forked six-phase diagram, at $116-118^\circ 30'$ in those with the dual three-phase diagram with interphase inductor.

The tests were carried out by varying the rotation speed of the set and maintaining the excitation anodes of the inverter commutator constantly lighted. The power delivered by the generator to the inverter, moderate while the generator voltage remains below a certain limit depending on the shape of the inverter characteristic, begins to increase ever more rapidly with increase in speed. The law of variation as a function of the rotation speed is shown by the solid curve in Fig. 3, for the diagram of the rotary set corresponding to that in Fig. 2, in which winding W is omitted, with the connection diagram of the forked six-phase inverter and for an angle of lag in grid polarization $\alpha = 105^\circ$. In examining the shape of this curve, Fig. 3 also shows a cubic parabola (dashed line). /58

The shape of the first curve is near enough to that of the second, within a wide range of variation in the rotation speed -- from 750-800 to over 2000 rpm. The set of rotary machines and the inverter were, in reality, only adapted to each other: with a purposely proportioned set, the coincidence should be better, and the range of variation in speed in which this

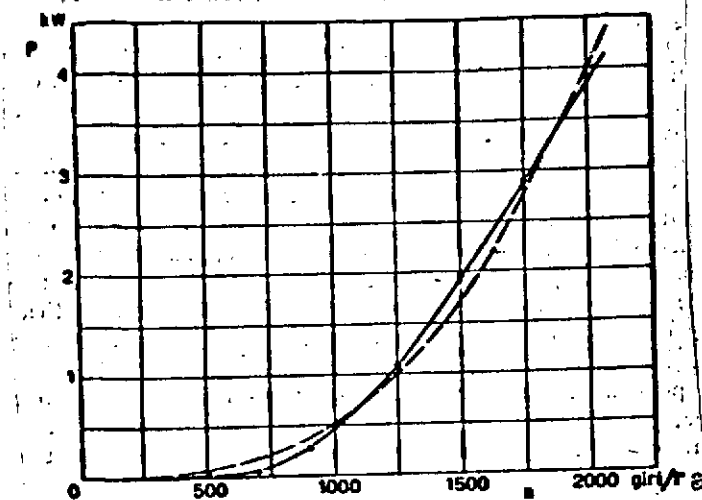


Fig. 3. Power delivered by the excited generator according to the diagram in Fig. 2, with winding W omitted, to the inverter with forked six-phase connection, with angle of lag in grid polarization $\alpha = 105^\circ$.

Key: a. rpm

portioning of the transformer and, especially, of the anode inductance, and finally, through the appropriate choice of the value of the angle of lag in grid polarization, inasmuch as this should be kept as great as possible in order to increase the operating power factor.

The shapes of the alternating current waves fed by the mercury-vapor inverter into the three-phase network are considerably affected by harmonics, as is well-known and as several oscillograms have confirmed, among others, between the electrical values. At any rate, the importance of the harmonics is moderate, while the network power prevails over that of single sets; nor should the possibility be forgotten of compensating the harmonics of the alternating currents connected in parallel, among them, most of the sets arranged with different connections that dephase the harmonics from one group to the other.

takes place should also be more extensive. Examination of the behavior of the set and the experimental tests show that both of these can be improved with a suitable choice of the diagram of the rotary machines (the one in Fig. 2 or the one in which winding W is omitted), with suitable proportioning of the magnetic circuits and excitation circuits of the different machines, influencing the inverter characteristic by means of suitable pro-

Apart from this disadvantage, the operation of the set is completely regular. The tests have shown its stability in the face of rapid variations in speed transmitted to it, both in the field of useful operation of the set and around its lower limit.

The possibility is also interesting of confronting the disadvantages deriving from possible sharp variations in voltage of the three-phase network. These would determine corresponding variations in the rectified voltage of the inverter and modifications of the power/rotation speed characteristic of the set, which would be the stronger, the closer the voltage values of the generator and the inverter. This can be avoided by generating the excitation voltage v_0 of the two exciters (Fig. 2) by a mercury-vapor rectifier fed from the same three-phase network, given the law of proportionality that yields the emf of the generator at v_0 .⁴ This solution also has the advantage of interrupting the generator excitation when voltage in the three-phase network is lacking and therefore excitation of the inverter and grid polarization voltage are lacking.

The type of set studied is suited for use and incorporation into a three-phase network with constant voltage and frequency, provided with its own reservoirs, without the need of accumulators, with power supplied for any wind velocity by a fixed-pitch air motor, and with no provision for a speed regulator.

There are in addition numerous other types of generator sets, both ac and dc, that have been studied previously, particularly recently in Italy. But apart from further types of groups that might be studied in the future, from the types already experimented with the impression is obtained that the problem of utilization of wind energy can be considered to be largely resolved by now,

⁴See Ref. [illegible].

as far as electrical generators are concerned. The same cannot be said for the aerotechnical part of the problem, especially in regard to the method of installing air motors and surveying wind resources in different regions. In regard to the aerotechnical part of the problem, it is to be hoped that other experiments will be successful in the manner of those few carried out in different countries, and, in the first place, success is hoped for those that will be initiated in Italy. Regarding the problem of aerial surveys, it is to be expected that the Government will soon furnish a solution.

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